The U.S. Climate Change Research Initiative (CCRI): Survey Of Research Strategies To Reduce Scientific Uncertainties

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At the Request of
President George W. Bush, Jr.

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PREFACE

"The U.S. Climate Change Research Initiative (CCRI): Survey of Research Strategies to Reduce Scientific Uncertainties" was presented to the President and the Cabinet by Secretary of Commerce Donald L. Evans in August, 2001. The document was prepared by the Department of Commerce as a first technical response to the President's June 2001 directive to develop improvements in science-based decision support methods for addressing climate change issues, supplementing the ongoing substantial body of basic research conducted by the US Global Change Research Program (USGCRP) during the preceding decade. The survey drew upon the draft of the ten-year USGCRP strategic plan developed in 2001, the 2001 climate research priority recommendations developed by the National Academy of Sciences (NAS) in an analysis requested by the President, and the broadly-noted research needs identified by the scientific community.

A technical working group principally composed of government scientists from the USGCRP participating agencies, and including assistance from several scientists in the academic community, prepared this document. The technical working group was convened to initiate the evaluation of options aimed at reducing scientific uncertainties and improving the information available for decision support related to climate change. Although this document provides a valuable record of potential strategies for research and observations, it was not edited for general publication, and it did not undergo interagency or independent scientific community peer review. Therefore the document should not be viewed as a completed or stand-alone statement of CCRI planning priorities. Instead, it is a first step in an iterative process aimed at the preparation of a widely reviewed CCRI/GCRP integrated planning summary that will involve substantial dialog with the scientific community and other stakeholder communities.

The ongoing development of the combined CCRI/GCRP program includes the following steps: (1) compilation and evaluation of a comprehensive inventory of climate- and global-change research programs currently being sponsored by the federal government agencies; (2) identification of criteria to prioritize current and proposed CCRI and GCRP programs; (3) identification of gaps and overlaps in current programs; (4) interagency prioritization of proposed research, monitoring and decision support initiatives that will best inform future climate and global change policy determinations, (5) publication of a comprehensive draft plan for the CCRI/GCRP program, for scientific and stakeholder review, and (6) publication of a final version of the CCRI/GCRP implementation plan that incorporates consideration of scientific and stakeholder reviews, and that includes schedules, deadlines and tracking metrics for the entire program.

This preface was prepared in May 2002. Please direct comments and questions to Dr. James R. Mahoney, Assistant Secretary of Commerce for Oceans and Atmosphere and Director of the GCRP/CCRI Program, by email at ***James.R.Mahoney@noaa.gov*** *or by telephone at 202-482-3567.*

THE U. S. CLIMATE CHANGE RESEARCH INITIATIVE: SURVEY OF RESEARCH STRATEGIES TO REDUCE UNCERTAINTIES

TECHNICAL SUMMARY

Background

In his June 11 speech at the Rose Garden President Bush announced the establishment of the U.S. Climate Change Research Initiative to study areas of uncertainty and identify priority areas where investments can make a difference. The President directed the Secretary of Commerce to set priorities for additional investments in climate change research, review such investments and, to improve coordination among federal agencies. He also committed to providing resources to build climate observation systems and proposed a joint venture with the EU, Japan and others to develop state-of-the-art climate modeling that will improve our understanding of the causes and impacts of climate change.

Furthermore, the Administration requested the National Academy of Sciences to review the Third Assessment of the Intergovernmental Panel on Climate Change (IPCC) and recommend research priorities to reduce uncertainties in climate science. The Academy report, entitled "*Climate Change Science: An Analysis Of Some Key Questions*", recommends the following:

A. Reducing the uncertainties in climate change projections by pursuing major advances in the understanding and modeling of:
   1. The factors that determine atmospheric concentrations of greenhouse gases and aerosols; and
   2. The so-called "feedbacks" that determine the sensitivity of the climate system to a prescribed increase in greenhouse gases.

B. Ensuring the existence of a long-term monitoring system that provides a more definitive observational foundation to evaluate decadal- to century- scale changes, including observations of key state variables and more comprehensive regional measurements of greenhouse gases.

C. Enhancing the research enterprise that deals with environmental-society interactions, including:
   1. Interdisciplinary research that couples physical, chemical, biological and human systems;
   2. Capability to integrate scientific knowledge, and its uncertainty, into effective decision support systems; and
   3. Research at the region and sector level that promotes analysis of the response of human and natural systems to multiple stresses.

The CCRI was developed in collaboration with the U.S. agencies involved in climate and global change research. Agency program administrators served as focal points and lead the development of the framework of this document. Approximately one hundred scientists, both in government and academia, contributed materials and participated in working group discussions. Five working groups were formed along thematic research areas. The proposed research initiatives emerged from a common sense of priority actions. Furthermore, the research initiatives reflect the priority areas that have already emerged in the draft U.S. Global Change Research Program 10-year strategic plan. The USGCRP began as a Presidential Initiative in 1989 and was codified by Congress in the Global Change Research Act of 1990 (P.L. 101-606).

The vision promoted in the CCRI planning is the effective use of scientific knowledge in policy and management decisions, and continual evaluation of management strategies and choices. Thus, the facilitation of adaptive management processes will be achieved by means of science products and tools developed to monitor the outcome of these processes. For example the improved climate models and future scenarios, together with information on carbon sources and sinks may be used to plan water resource needs and power plant locations in given metropolitan areas. The model products will be used to project the results of management options, such as economic and demographic input to the integrated models, in terms of the environment, the economy and human health. The monitoring system that will be in place will continually evaluate and assess the projected climate and ecosystem impacts and will lead to improvement in both management strategies and the decision support tools.

Perspective and Document Organization

The research initiatives identified in this report aim to make rapid progress in reducing the uncertainties in our knowledge of climate change by a focused investment in high priority areas over the next five years. The NAS recommendations are comprehensive and outline needs for research that will extend far in the future. For example, the global observing system in support of long-term climate modeling and prediction that they recommend will obviously require investments that last longer than five years. The specific proposed actions have a dual aim: (1) to reduce the present uncertainties in climate science and develop the enabling modeling capabilities, and (2) to develop research and data products that will facilitate the use of scientific knowledge to support policy and management decisions.

This survey of research initiatives is organized according to the above two goals. The research and management objectives are outlined, followed by a recommended implementation strategy in each case. It is essential that this CCRI initiative take place in the context of the broader global change research program that is ongoing in federal agencies. The US Global Change Research Program provides the continuing study of all of the complex, interrelated global change aspects that will allow the CCRI initiative to be successful, while continuing to address both long-term and short-term NAS recommendations. For this reason, a brief discussion of ongoing plans and activities is provided in order to highlight work most closely related to the proposed tasks, which will complement or accelerate existing activities, followed by some key deliverables. Other ongoing GCRP work, even though critical to sustain a climate change research program, is not presented here in the interest of keeping this document at reasonable length. Furthermore these plans were developed assuming the continued conduct of ongoing climate change programs.

In addition to identifying science priorities, the NAS has recommended changes to the existing coordinating mechanisms. Many discussions among the scientists also pointed to a need for new management strategies, as the feasibility and the implementation of the plans were considered. In particular, discussions on developing and improving climate observations and modeling capabilities were strongly linked to a more centralized management structure. Following the President's direction to "review investments in climate change research, and to maximize coordination among federal agencies", a separate recommendation is being developed to address improved management structures for climate programs. A specific management plan for the implementation of this initiative will be proposed within the overall management context.

Initiative Products

The **ultimate products** of these studies will be products for use by policymakers and decision-makers, as well as by all global and climate change stakeholders and interested members of the general public. The studies aim to answer questions posed by the Administration, which were incorporated into the statement of task for the NAS study. Some examples of key suggested products include:

- Global and regional maps and inventories of greenhouse gases and particulate matter that force climate change. Measurements and studies of the amount of carbon being taken up by the North American biosphere will provide an essential assessment of the effectiveness of carbon management strategies and critical input to discussions of carbon credits.
- A wide variety of data products that will constitute an improved quality climate record. The climate record is a time series of key physical variables, such as temperature and precipitation, at monitoring sites or aggregated at regional and/or local levels. These data are essential input to climate models, therefore key to predicting future climate. The climate record itself is valuable information for industrial planning in sectors such as electric utilities, transportation, construction, insurance, and many others.
- Improved **"scenarios"** of future human activity as input to climate change projections. At present the scenarios being used by the Intergovernmental Panel on Climate Change (IPCC) do not include all of the important particulate aerosols that affect climate. Extending the emissions scenarios to include this wider range of relevant anthropogenic inputs is essential, and IPCC has called for such research on scenarios. In addition the current set of IPCC scenarios includes already dated population forecasts, a confusing combination of business as usual

and policy intervention scenarios, and a perhaps unwarranted optimism about economic growth in much of the developing world.

- An evaluation of the relative likelihood of the scenarios. The capability to assess the plausibility or likelihood of either the individual scenarios, or a range of scenarios is one of the factors to reduce the range of uncertainty in climate change assessments.
- A series of nationwide studies conducted during the next five years that explore the: effects of climate change on ambient air quality in major U.S. metropolitan areas; effects of changes in air quality on human health; extent to which wastewater treatments costs may be affected by climate change and changes in extreme precipitation events; effects of climate change and climate variability on drinking water quality; effects of climate change on water-borne diseases in metropolitan areas; and effects of climate change and climate variability on weather-related morbidity.
- Model products that will allow for improved projections of future climate.
- Tools that will provide the capability to generate future climate projections under a variety of scenarios and the associated uncertainties.
- Improved knowledge of natural *vs.* human caused climate change.
- New tools for integrated assessment and risk management;
- Scientific studies that reduce key uncertainties about impacts of climate change;
- New programmatic mechanisms for identifying, supporting, and evaluating research, which include both regional and national decision support perspectives.
- Evaluations of the potential impacts of climate change on precipitation and therefore on agriculture, water availability and other impacts related to precipitation.
- An understanding of the potential for extreme weather events as a result of climate change or of abrupt climate change is clearly an important consideration for policy makers in determining whether more aggressive action is necessary to reduce anthropogenic climate forcing.
- Decision-support tools to help public health officials determine appropriate adaptive response strategies, and to evaluate the extent to which these responses at the societal or individual level could reduce the impacts of climate change on human health and increase the resilience of the public health care system to climate change.

As previously stated, the proposed studies should produce products for policymakers and decision makers. For example, studies of the amount of carbon being taken up by the North American biosphere will provide critical input to discussions of carbon credits. Studies of the regional impact of changes in hydrology will provide critical information to regional water managers on expected changes in water availability. However, to develop these decision support products we will need critical intermediate products: studies of key processes that will reduce uncertainty, observations of priority components of the climate system, and improved global climate models. For example, climate models that accurately include the role of aerosols and water vapor in climate forcing and feedback mechanisms should substantially improve our ability to determine the relative importance of reducing aerosol emissions as compared to CO2 and methane emissions.

Coupling these model studies with studies of regional processes will also provide much clearer evidence of the impact of climate change on precipitation and therefore on agriculture, water availability and other impacts related to precipitation.

Models of future climate assume certain **scenarios** of future human activity as inputs. At present the scenarios being used by the IPCC do not include all of the important particulates aerosols that affect climate. Extending the emissions scenarios to include this wider range of relevant anthropogenic inputs is essential and IPCC has called for such research on scenarios. The scenarios will be important determinants of the perception of the problem to be solved.

The most significant limitation of the current set of scenarios is the lack of information on the **relative likelihood of the scenarios**. If the objective is to reduce the range of uncertainty, finding a technically valid way to assess the plausibility or likelihood of both the individual scenarios and ranges of scenarios is very important. This is an area needing creative initiatives, because most existing tools have well recognized technical flaws.

Carbon is the basis for the food and fiber that sustain human populations. It is the primary energy source that fuels human economies, and it is a major constituent of the greenhouse gases accumulating in the Earth's atmosphere that are the basis for potential changes in global climate. Carbon dioxide (CO_2) and methane (CH_4) concentrations in the atmosphere are now higher than they have been for over 400,000 years. Combustion of fossil fuels and land clearing (reducing forests, grasslands and vegetative cover) during the past 150 years are the sources for most of this increase. Approximately half of the carbon dioxide released to the atmosphere annually by human activities remains in the atmosphere. The other half is taken up by trees and other plants on the land, and by plants and chemical processes in the ocean. Since trees, plants, soils, and the ocean also release carbon to the atmosphere as part of their overall functioning in the Earth's carbon cycle, it is of great importance to quantify the size, power, and longevity of these sinks. **Active management of the carbon cycle** offers opportunities to offset carbon emissions by enhancing the storage of carbon in plants, soils, and forest products as well as in the oceans, although the time scales over which these practices can remain effective are unknown. The nation and the world are entering an era in which carbon cycle issues lie at the core of several policy debates centered on future climate change and its consequences for humans.

One of the major challenges for global climate models is the accurate characterization of the **multiple processes of the ocean and atmosphere** that are important for projecting changes in climate. These processes can alter or amplify the effects of greenhouse gases. In the geologic past they have also been characterized by abrupt changes that had far-reaching effects on climate.

Societies and ecosystems are often most vulnerable, and least resilient, to the environmental stresses produced by **extreme weather and climate** events. The need for improved information on such events, particularly at regional and local scales, is one of the highest priorities for users of climate information. Major droughts, floods, heat waves, hurricanes, and storm surges are examples of extreme events that have major economic and social impacts, and whose frequencies, intensities, and geographical distributions may change in the future.

Deliverables produced under the initiative are expected to include:

- Coupled research and information systems that improve decision making to reduce vulnerability and enhance resilience to climate change;
- New tools for integrated assessment and risk management;
- Scientific studies that reduce key uncertainties about impacts of climate change;
- Reports to the nation (both scientific and for the general population) that examine national-level policy implications; and
- New programmatic mechanisms for identifying, supporting, and evaluating research, which include regional decision support and national policy making perspectives.

Air pollution continues to be a widespread public health and environmental problem in the United States. The evaluations of effects of climate change on air quality will provide baseline information about ozone and particulate matter under conditions of climate change that will be used to derive health effects estimates. The initiative will also produce decision-support tools to help urban air quality managers determine whether climate change will make it more or less difficult for them to meet ambient air standards, and to evaluate what opportunities exist to build resilience to these future changes.

Water quality is already affected by factors other than climate change (e.g., nutrients, sediments, microbial pathogens, pesticides, and other toxic pollutants) and alterations in freshwater habitats, stream flow, and water temperatures. These influences on water quality may be exacerbated or ameliorated by climate change, climate variability or land-use change. The results of this initiative will assist water quality managers in **urban and metropolitan areas** to evaluate the extent to which climate change will make it easier or more difficult for them to maintain water quality as the climate changes, and to identify opportunities to adapt to change.

One expected benefit of these initiatives is improved capacity to reduce damages associated with **extreme weather events** and to incorporate understanding of extreme events into our broader concepts of sustainable economic development. We envision contributions to disaster relief efforts, where there is considerable interest in moving from after-the-fact aid to the pre-positioning of plans and resources. Early warning systems, and public and private sector urban, water, and land use planning are also clients for the products of this effort. This initiative would also provide additional means for operational climate forecasters and information providers to evaluate their products and ensure that their investments are targeted on matters of highest concern to vulnerable populations.

Decision-support tools will also be developed to help **public health officials** determine appropriate adaptive response strategies, and evaluate the extent to which these responses at the societal or individual level could reduce the impacts of climate change on human health and increase the resilience of the public health care system to climate change.

To fully understand the implications of improved climate change understanding requires that that knowledge be **integrated** with other knowledge, particularly with regard to the economy, and the breadth of forcing functions. Without a full systems analysis context it will be impossible to realize the full benefits of this research.

Comprehensive modeling is a central and critical element of climate research. Over the last two decades, the climate research community has sustained significant progress in the continuing development and application of climate models. Nevertheless, the current organizational structure of the U.S. modeling effort has not fully supported the delivery of model products that are especially important for making climate simulation and prediction more usable and applicable to the broader research, assessment and policy communities. The U.S. agencies have initiated planning and activities towards forming the basis for a longer-term solution that maintains the pace and progress of the basic research enterprise while simultaneously creates a path for the rapid exploitation of new knowledge in model products.

RESEARCH STRATEGY OPTIONS

In response to the President's CCRI directive, the following research strategy options are recommended for consideration. The summary in the remainder of this document follows the outline of the three categories of NAS recommendations, identified above as A, B and C.

A. REDUCE THE UNCERTAINTIES IN CLIMATE SCIENCE

We recommend high priority studies to address the most important unknowns in **climate forcing** including studies of the chemical and radiative properties of aerosols and in **climate feedbacks**, including studies of the role of clouds, water vapor, precipitation and evaporation, and aerosols in feedback processes. Global climate models used for prediction of future climate are also sensitive to emissions scenarios. We recommend the development of new **emissions scenarios** that recognize the importance of aerosols and greenhouse gases other than carbon dioxide and methane. In order to discern climate change due to human activity from natural variability, we recommend studies that will extend and improve predictions of natural variability. This will also substantially improve inference from climate models.

1. <u>Climate Forcing: Atmospheric concentrations of greenhouse gases and aerosols</u>

a. Develop reliable representations of global and regional climate forcing by atmospheric aerosols.

Aerosols and tropospheric ozone play unique, but poorly quantified, roles in the atmospheric radiation budget. This occurs, in part, because both aerosols and tropospheric ozone are short-lived and have spatially and temporally heterogeneous distributions. The role of aerosol particle radiative forcing is complex and current understanding of the problem is fragmented. There are two distinct, but related effects of aerosols. The first is the direct effect of particles on the radiation budget of the planet; the second is the effect of changing particle concentrations on cloud properties (the indirect effect) and the subsequent effect of those clouds on the radiation budget.

Research Objectives

- Develop global aerosol climatology with improved representation of regional distribution of aerosols by major type and radiative properties. Establish the climatic importance of radiative-forcing from aerosols that absorb solar radiation, such as carbonaceous and mineral dust aerosols.
- Determine the linkages between ozone and aerosol sources and sinks to global distributions, and therefore to radiative forcing, in order to understand regional impacts of current and projected concentrations.

Proposed Strategy

- Establish new and augment existing in-situ monitoring sites, including aircraft sampling, in and downwind of major population areas (e.g. Asia, Eastern North America and South America) to establish temporal and spatial distributions, trends, and aerosol chemical and radiative properties.
- Integrate the available remote sensing (satellite and ground-based) and in situ data into a single product of known and uniform data quality.
- Develop integrated chemistry, aerosol and climate models that combine basic ozone and aerosol chemistry and physics with transport and removal. Integrated models can be used to study regional patterns, evaluate our understanding of source and sink processes, and project future distributions
- Conduct focused field campaigns and/or appropriate laboratory experimentation to experimentally assess the importance of aerosol concentration and composition on cloud microphysical and radiation properties and on precipitation.
- Develop cloud models with comprehensive aerosol-cloud microphysics to determine areas of uncertainty and those processes that are most critical to the alteration of cloud properties.

Ongoing plans and activities

The specific observations and research proposed here will complement the more comprehensive atmospheric chemistry studies proposed as part of the ongoing USGCRP work plan. For example, the USGCRP plan emphasizes the importance of characterizing the distribution of all major aerosol species and their variability through time, the separate contribution of aerosols from various human activities, and the processes by which the separate contributions are linked to global distribution.

In the past few years, several major field experiments in the Indian Ocean, Asia, and Africa have been carried out primarily to address the direct effect aerosols play through the scattering of radiation. These experiments will continue to contribute to our understanding of aerosol processes in the atmosphere and aerosol forcing of the climate. Similarly, the MODIS, MISR and OMI instruments on NASA satellites are providing a vastly improved assessment of the global aerosol. The new AQUA satellite will also have a MODIS instrument. At present, NPOESS instrument and algorithm development includes observing the refractive index and size distribution of aerosols, and through those, inferred measurement of the chemical composition of aerosols. These measurements can be acquired as early as the NPP mission, and together with vertical profile aerosol distributions data from EESP-3 CENA will constitute an unprecedented observational record, capable of addressing the indirect effect of aerosols. Work funded under the GACP is synthesizing observations made in several programs and also linking models and observations.

Deliverables

- Identification and evaluation of role of aerosols that absorb solar radiation such as black carbon and mineral dust
- Evaluation of the regional impact of current and projected concentrations of ozone and aerosols on climate

b. Understand future emissions of radiatively active gases and aerosols

The discussion of climate forcing and feedback in the preceding paragraphs illustrates that the range of human system activities that are relevant for understanding future climate is much wider than fossil fuel use and methane emissions. In addition to the emissions of the usual greenhouse gases it is important to understand direct emissions of particulates. These may include black carbon/soot emissions from biomass burning, aerosol precursors such as SO_2, and various forms of nitrogen emissions that may affect biological productivity. Moreover, deforestation affects transpiration, surface roughness, and runoff.

Proposed Strategy

- Extend the control strategy projections applied to SO_2 emissions in the recent IPCC scenarios to all relevant local environmental pollutants.
- Improve the modeling of agricultural activities, including long-term growth in productivity and its impact on land use and conversion, and the ability to provide sufficient nutrition to developing countries.
- Improve population forecasts, including the important determinants of total completed fertility, death rates, and migration. These determinants must reflect an integration of the demographics models and socio-economic models.
- Revisit with care the determinants of long-term demands for food and energy, the two economic activities most responsible for greenhouse gas emissions.
- Develop tools to provide more disaggregated results for relevant emissions and levels of economic activity.

Ongoing plans and activities

The current set of IPCC scenarios includes population forecasts that need updating, confusing combinations of business as usual and policy intervention scenarios, and perhaps unwarranted optimism about economic growth in much of the developing world. Using improved, integrated and more comprehensive assessment models to develop a revised set of emissions scenarios would be a very helpful step.

Deliverables

- Improved, more realistic climate change scenarios, and the relative likelihood of these scenarios, from integrated assessment models projecting future atmospheric greenhouse gas concentrations.

c. <u>Inventory carbon and model sources and sinks</u>

Research objectives for carbon cycle science in the next decade include combinations of modeling, inventory, observations, process research, and assessment, integrated according to topic areas that represent some of the field's greatest areas of uncertainty. Scientific understanding of the carbon cycle has now advanced to the point where a small number of targeted investments can yield major returns in five years. The proposed investments in carbon cycle research will provide decision-makers, resource managers and the public with solid, quantitative information on the role of the U.S. as both a source and a sink for carbon. Policy makers and resource managers will have useful assessments of the potential of U.S. forests, soils, and coastal systems for carbon sequestration and the first reliable estimates of the time scales over which these managed sinks could be maintained. Decision support tools will be available to explore impacts of energy policies, land use policies, and climate change policies on management options. Resource managers will have more efficient and reliable methods for inventorying forests, rangelands, and croplands and assessing the impact of various management practices on crop yields, timber volume, and soil fertility.

Error budgets in the global carbon balance will be significantly reduced, and policy makers will have a better understanding of where the global hot spots of carbon uptake and release are located. It is unlikely that this information will be resolved at a national scale – except for very large nations – but it will be useful for international negotiations and identifying regions where mitigation activities are most needed or would have the most impact. Similarly, projections of climate change and the scenarios used to inform assessments will be improved, and additional insight into the societal risks of climate change and human efforts to mitigate climate change will be derived.

Research Objectives

- Quantify the North American region's carbon sources and sinks, describe the natural and human system processes controlling changes in them, and document North America's contribution to the Northern Hemisphere carbon sink.

- Reduce uncertainties in regional patterns of carbon sources and sinks on a global scale.
- Quantify the main mechanisms resulting in sub-decadal variability in natural fluxes of carbon between ocean and atmosphere, and land and atmosphere.
- Quantify the role of land management and land use practices on storage of carbon.
- Assess options for managing carbon in the environment, their effectiveness, and their impacts on the environment and human activities for purposes of mitigating climate change.
- Provide more realistic model projections of future atmospheric carbon dioxide concentrations and scenarios of future climate change.

Proposed Strategy

- Integrated North American Carbon Study -- An intensive focus on North American land and adjacent ocean basin carbon sources and sinks, to improve monitoring techniques, reconcile approaches for documenting carbon storage, and elucidate key controlling processes and land management regimes regulating carbon fluxes from the land and ocean.
- Carbon Observations in Under-Sampled Areas **--** A focus on augmenting observations of globally relevant parameters in key under-sampled oceanic and continental regions around the globe, selected to reduce high uncertainty in current flux estimates (such as the Southern Ocean, continental tropics and boreal regions). Required to achieve deliverable: Multiple Constraint Modeling and Data Assimilation to develop and support framework to utilize carbon-related measurements in the most efficient and systematic way
- Process Studies and Manipulative Experiments -- Terrestrial and oceanic process studies with changing environmental factors such as elevated CO_2, enhanced nutrients, water stress, temperature, manipulated to discover managed and unmanaged ecosystem sensitivity to potential global changes.
- Carbon Management Strategies -- Empirical, process and modeling studies to elucidate the potential decision pathways and develop systems for managing carbon sources, such as fossil fuel consumption, and carbon sinks, such as agricultural and forest management.
- Dynamic carbon-climate projections --Improvement in model parameterizations, incorporation of human decision pathways, and coupling of dynamic carbon cycle models to global climate models to more realistically project future CO_2 and related greenhouses gases.

Ongoing plans and activities

Significant investments over the past decade have resulted in an unprecedented opportunity to study the carbon cycle over a scale not previously attempted-- the continental/basin scale. Observational resources such as the USDA forest and soil inventory, Ameriflux, CMDL tall towers, Atlantic and Pacific ocean time series and ships of opportunity, vegetation and ocean color remote sensing have all contributed to a better understanding of the components of the carbon cycle over North America and adjacent basins. Building on our existing observational and research activities, we recommend enhancement of sensors on existing networks, augmentation of sites in networks in some cases, new observations to connect the scales of activity, and innovative new diagnostic modeling frameworks to ensure that data are being used in the most efficient manner to constrain regional patterns of sources and sinks.

To achieve adequate resolution of global carbon sources and sinks on a regional scale in the next five years, we will build on our pilot capabilities to observe carbon storage in land and ocean and exchanges with the atmosphere. New observational locations will be deployed as determined by optimal sampling schemes and requirements for model improvement. A number of pioneering efforts have successfully been launched in the past decade to study the impact of rising carbon dioxide on the growth and flows of carbon in a variety of ecosystems, including large forest areas and savanna ecosystems. In addition, great strides have been made in understanding key processes limiting phytoplankton growth in the ocean, which is a factor in uptake of carbon dioxide by the ocean. Building on this work in the next five years we will quantify ecosystem respiration on land, and study the responses of ecosystems to multiple stresses.

Carbon management is a relatively new topic but an increasingly relevant one as nations consider options for responding to climate change. The next critical step in understanding managed ecosystems is understanding the role that agricultural and forestry management practices play in carbon storage, and how multiple changes in environmental factors may affect carbon storage, pest distributions, and crop production. The recommended priorities target steps for continued improvement on the investments of the past few years.

Research in the past decade has focused on improving dynamic models of the components of the carbon cycle. A quantum leap forward is possible by coupling dynamic component models to existing and improved general circulation models.

Efforts to improve the measurement and quantification of carbon storage and fluxes will be aided by new and emerging technologies. Routine quantification of changes in carbon sources and sinks around the world will require new remote sensing capabilities for measuring atmospheric carbon dioxide and estimating biomass.

Deliverables

- An analysis and quantification of regional carbon sources and sinks and prospects for carbon management in U.S. managed systems for the 1/3 of the Northern Hemisphere centered on North America – land, ocean, atmosphere, and human system;
- Estimates of carbon flux strength in currently highly uncertain regions, thereby reducing uncertainty both for regional budgets of carbon flux as well as global estimates of uptake, with the ability to reveal key gaps in our process understanding and observational system necessary for improving dynamic prediction models.
- Identification of critical potential feedbacks in the regulation of carbon storage and fluxes by the land and ocean ecosystem, including sensitivities to climate, species distribution shifts, and circulation pattern changes.
- Analysis of options available to decision-makers for management of the carbon system, assessment of on-going management practices, and development of management systems for deployment by landowners.

- o Improved, more realistic climate change scenarios from prognostic models projecting future atmospheric greenhouse gas concentrations and carbon-climate interactions and feedbacks.

2. Climate Feedbacks: Climate system sensitivity

a. Develop improved representations of clouds, precipitation and water vapor in climate models

Water plays a key role in the radiative balance of the atmosphere: in the vapor phase, it is the most important of the so-called "greenhouse gases"; in condensed phase (both liquid and ice clouds) it affects both vertical heating profiles and geographic heating patterns. Results from climate models suggest there will be an increase in water vapor as the climate warms. Water vapor is a natural greenhouse gas and its increase produces a positive feedback that approximately doubles the warming due to increased concentrations of anthropogenic greenhouse gases. Predictions of global warming vary in large part because of differences in the way that the various feedback processes are represented in the models. It is ironic that among the uncertainties regarding feedbacks in the climate system, those associated with the representation of water vapor, the most important greenhouse gas, and cloud processes are the greatest. For example, it is not known how the amount and distribution of clouds will change, both vertically and horizontally, as the water vapor in the atmosphere increases. More importantly, we do not know the impact on climate of the associated changes in radiative forcing and precipitation. The feedbacks could be positive or negative. Another related uncertainty is associated with the detrainment of moisture from clouds as a function of height. This is particularly important in the tropical upper troposphere where the radiative impact of water vapor (or ice crystals) could be substantial and significant questions remain regarding the nature of troposphere and stratosphere exchange.

Basic understanding of the processes that control the atmospheric water vapor and clouds must be improved and incorporated into models. Better representation of the distribution of water vapor is critical given its contribution to temperature increases as an active radiative gas as well as its role in cloud formation. Because the physical processes responsible for the transport of water vapor or cloud formation occur at scales that are not resolved by climate models, they must be parameterized. Reducing the uncertainties due to the representation of cloud and water vapor in climate models will require better (three-dimensional) observations, targeted process studies, and model improvements.

Research Objectives

- o Improve understanding of water vapor and water condensate concentrations and source and sink processes in the upper troposphere and lower stratosphere, particular in the tropics
- o Provide a framework in which cloud parameterizations can be evaluated rigorously against atmospheric data and cloud model sensitivities can be assessed

Proposed Strategy

- Combined *in situ* and remote sensing and process studies of the injection of water vapor in the upper troposphere by convection and studies of stratospheric-tropospheric exchange in the tropics
- Analysis of detailed, quantitative, three-dimensional data on cloud amount and height, phase and water content, dynamics, cloud radiation and precipitation processes for a variety of synoptic regimes using a combination of ground-based and satellite remote sensing
- Tests of cloud parameterizations in the framework of process-resolving cloud ensemble models
- Tests of cloud parameterizations against observations in the framework of operational regional or global atmospheric circulation models
- Tests of climate model sensitivity to three-dimensional cloud representation employing cloud-resolving models

Ongoing plans and activities

Research on water and clouds will have to be closely linked to investigations of aerosols. A major source of uncertainty related to clouds is the indirect effect of aerosols that serve as the condensation nuclei for cloud droplets. Aerosols can affect the brightness (albedo) of clouds as well as cloud thickness, lifetimes and precipitation characteristics.

While the studies that we describe here will substantially improve our understanding of feedbacks, other studies proposed as part of "A Plan for a New Initiative on the Global Water Cycle" and the USGCRP Strategic Plan will be critical to predicting the impact of climate change on precipitation and water availability, for example, determining long term trends in the global water cycle including the character of hydrologic events and their causes; developing the ability to bridge climate and weather modeling; and determining the relationship between the water cycle and biogeochemical/ecological processes.

Deliverables

- New, observationally-tested cloud parameterizations for global climate models

b. <u>Evaluate Polar Regions for the potential of rapid and extensive climate feedback</u>

It has been argued that Polar Regions, especially the Arctic, are the most sensitive areas for detecting global change and have great potential for causing abrupt climate change. Modeling studies indicate that under a representative global warming scenario, temperature increases will be amplified in the Arctic due to feedbacks involving the snow and ice cover that, in turn, feedback to global climate. First, the Arctic Ocean's stratification and ice cover provide a control on the surface heat and mass budgets of the north polar region, and therefore on the global heat sink. If the distribution of Arctic sea ice were substantially different from the present, the altered surface fluxes would affect both the atmosphere and the ocean and would likely have significant consequences for regional and global climate. Second, the export of low-salinity waters out of the Arctic Ocean, whether in the form of liquid or desalinated sea ice, has the potential to influence the overturning cell of the global ocean through control of convection in the subpolar gyres. Third, Arctic soils serve as significant reservoirs of carbon dioxide and methane and warming of the region could result in increased atmospheric emissions of these greenhouse gases.

For the past decade or more, climate-driven environmental changes in the Arctic have been severe, and there is a strong possibility that these changes will continue into the future and cause consequences throughout the Northern Hemisphere. Regardless of the causes for these changes, the decade-long warming of the Arctic also has the potential for resulting in abrupt climate change associated with rapid melting of much of the Arctic sea ice or extensive thawing of permafrost and release of greenhouse gases. Recent measurements of sea ice thickness in some parts of the Arctic show that it is only 40% of the thickness 50 years ago. Continued thinning could lead to rapid melting and breakup of the ice. Longer and deeper permafrost thaw could release large quantities of CO_2 and methane. The greatest uncertainties in our ability to judge the likelihood of these two scenarios are, respectively, the restricted area of available sea ice thickness measurements and the poor coverage of permafrost stations.

In the Antarctic, the West Antarctic ice sheet (WAIS) is the only remaining marine ice sheet from the last glacial period. The increasing number of major tabular icebergs that calve from the ice sheet has led to concern that the ice sheet may be susceptible to runaway "grounding line retreat", leading to rapid disintegration. This would result in rapid sea level rise. Were the WAIS to completely melt, the water released is sufficient to raise global sea level by 5-6 meters. The likelihood of such a scenario, and the ice sheet's sensitivity to climate forcing are topics of ongoing research. The grounding line position and net balance are key parameters for observing ice sheet changes. Those data, when combined with accurate basal environment information, are critical for supporting model-driven hypotheses concerning the response of the WAIS to climate change and sea level change.

The Amundsen Sea Embayment (Pine Island Bay/Thwaites Glacier area) is the only major West Antarctic drainage not buttressed by a large ice shelf and thus is the drainage most likely to participate in a collapse. Recent observations using interferometric SAR and repeat satellite altimetry show a speed-up, thinning, and grounding-line retreat of ice flowing into Pine Island Bay. Model studies focused on this drainage are needed to assess the possibility that the ongoing thinning will lead to retreat from a prominent bedrock sill, which in turn might trigger major changes in the ice sheet, contributing to sea level. However, available radar data do not provide sufficient geometric detail or information on internal layers and basal conditions to allow confident modeling.

Research Objectives

- Measure sea ice thickness in the Arctic ice margin environment for five years to determine whether thinning observed in the central Arctic is present across the entire basin;
- Measure permafrost temperature and thaw patterns in sufficient detail for five years to establish regional thaw patterns;
- Establish the mass balance and ice dynamic regime of the Pine Island/Thwaites drainage system of the West Antarctic ice sheet; and

- o Quantify the boundary conditions of the Pine Island/Thwaites drainage system in a fashion suitable for 3-D ice sheet modeling and develop atmosphere/ocean/ice models to assess the likely stability of this part of the ice sheet.

Proposed Strategy

- o Expand the network of ice-ocean buoys, especially in the Arctic ice margin, and surface observations to track changes in ocean/ice/lower-atmosphere temperature, ocean salinity and circulation, and sea ice thickness;
- o Expand the arctic-wide network of permafrost stations and boreholes to sufficient numbers to determine regional thaw patterns that reflect the pace of climate change;
- o Expand the network of automatic weather stations over the West Antarctic ice sheet to include the Pine Island/Thwaites ice drainage system and establish a program of mass balance studies (accumulation stakes, shallow snow pit and ice core studies, short-pulse ground penetrating radar measurements to identify near surface layering) and ice dynamics measurements (e.g. ice velocity and surface elevation- using both satellite data and ground based measurements); and
- o Collect geophysical data (surface and bed elevation, ice thickness, bed roughness, internal layering, gravity anomalies, magnetic anomalies) to provide a better picture of the subglacial topography, using airborne remote sensing techniques. These data will provide input for a new generation of coupled ice sheet-ocean-atmosphere models.

Ongoing plans and activities

Enhanced meteorological observations are also a key to reducing uncertainties in the response of the Polar Regions to climate change and are addressed in the Climate Observing System section of the Climate Change Research Initiative. Proposed integrated Arctic science studies, such as SEARCH, will be critical to putting the measurements proposed here into a larger context.

Deliverables

- o An assessment of the likelihood of large-scale polar sea ice thinning or of an ice-free Arctic;
- o An assessment of the likelihood of large-scale release of greenhouse gases presently sequestered in permafrost; and
- o An assessment of the likelihood of West Antarctic Ice Sheet collapse.

c. <u>Extend and improve predictions of climate variability.</u>

Incorporating improved understanding of mechanisms producing different patterns of climate variability into climate models provides the potential to extend and improve predictions of climate variations and their regional impacts. ENSO is known to induce major impacts on weather and climate extremes such as hurricanes, floods, and droughts in many regions of the globe. One of the major accomplishments of recent climate research has been the successful application of ENSO predictions several seasons in advance; however, while the models have demonstrated some skill in predicting ENSO patterns in the tropical Pacific, they cannot predict the remote, non-local, impacts.

Scientists have also identified other important patterns of natural climate variability such as the North Atlantic Oscillation (NAO)/ Arctic Oscillation (AO), and the Pacific Decadal Oscillation (PDO). These modes involve both internal and coupled atmospheric and ocean dynamics as critical components, and models differ in their ability to simulate them. For example, it is still an open question whether NAO is an uncoupled atmospheric process or a process coupled to the ocean. All of the modes influence weather systems substantially. We do not yet know to what extent these natural modes of climate variability are predictable, nor how a changing climate will affect them, or the impacts such changes might have on regional climate, extreme weather events, or the potential for abrupt global climate change. One of the major challenges for global climate models is the accurate characterization of the multiple processes of the ocean and atmosphere that are important for predicting changes in climate.

Observations of current and past climates will play an important role in improving the characterization of physical processes in the ocean, atmosphere, land surface and cryosphere, and in validation of climate models. The need for refining, extending (both backwards and forwards), and analyzing long-term observational records to better discriminate natural climate variability from global change is self-evident. Field programs and modeling experiments will be used in identifying key physical processes and regions that need to be better observed and monitored, which will help in designing the future climate observing system.

Changes in ocean circulations, such as a suppression of the large scale thermohaline "conveyer belt" that transports heat, would greatly impact the natural climate of the U.S. Gulf states, the North Atlantic, and western Europe. Paleoclimate data suggests the thermohaline circulation of the North Atlantic can shut off over a matter of decades resulting in significant shifts in the distribution of surface temperature, rainfall and storms. The response of the thermohaline circulation under a changing climate is a major issue with vast potential consequences, including the possibility of abrupt climate transitions, such as those observed in the historical and geologic past. Modeling studies indicate that a potential response to changes in global temperature and the melting of high-latitude ice is a rapid reorganization of the three-dimensional ocean circulation. A first step is to develop methods to determine the likelihood of abrupt climate change and to identify critical indicators/evidence needed to assess whether we are currently experiencing an abrupt change.

Research Objectives

- Simulate with climate models the weather and climate extremes observed as a result of the ENSO cycle.
- Determine the mechanisms controlling variability of the high air-sea heat flux regions adjacent to subtropical western boundary currents by a field experiment coordinated with high-resolution ocean modeling

- Characterize the temporal variability and spatial structure of the Indonesian Through-flow, the primary link between the western Pacific and eastern Indian Oceans, a poorly understood component of the meridional overturning circulation, and a potential influence on the Asian monsoon.
- Test competing hypotheses forcing the NAO/AO, e.g., tropical and/or midlatitude SST, stratospheric dynamics, sea ice, by means of modeling and empirical studies.
- Develop a modeling strategy for resolving weather phenomena in climate change projections by combining high-resolution global or regional fine-mesh models with coarser representations suitable for long-term integration.
- Develop methods for determining the likelihood of abrupt climate change, such as the collapse of the ocean thermohaline circulation or the loss of the polar ice cap, and the expected global and regional manifestations of such changes.

Proposed Strategy

- Analyze and clarify connections between observed ENSO variations and the geographic distribution, frequency, and intensity of weather systems (intense mesoscale systems) through diagnostic studies of global and regional data.
- Develop a modeling strategy for incorporating interactive simulations of ENSO and weather systems dynamics, at the required spatial resolution, by alternatively switching from relatively coarse resolution to mesoscale-resolving spatial grids, or the use of embedded regional fine-mesh models.
- Deploy Lagrangian and Eulerian instrumentation in high flux regions of the ocean, together with ship-based surveys, acoustic thermometry and a buoy-based meteorological observing array. Exemplars include, the regions near the Kuroshio Extension in the N. Pacific, the Gulf Stream Extension and North Atlantic Current in the N. Atlantic and the Brazil/Malvinas Confluence in the S. Atlantic.
- Conduct simultaneous measurements of flow through the northern Indonesian passages, flow through southern Indonesian passages, and the hydrography of the Banda Sea and analysis with contemporaneous data about seasonal atmospheric and oceanic patterns in the western Indian Ocean and in the western Pacific. Ideally this should be an international effort and include scientists from the U.S. and Indonesia.
- Conduct a focused field experiment, using combined Eulerian and Lagrangian instrumentation, to understand processes that modulate the air-sea heat flux in the NAO region.
- Conduct a hierarchy of sensitivity experiments to determine the relative role of tropical, mid-latitude SST and sea-ice in climate variability due to NAO/AO.
- Couple a high resolution climate model with a stratospheric model of high enough resolution and complete enough physics to represent the upper atmospheric dynamic processes believed to drive the NAO/AO.
- Conduct a series of model experiments designed to improve the coupled model physics, leading to improved simulation of the NAO/AO.

- o Apply models to predict future climates, with and without human-induced forcing, to examine the impacts of the forcing on the characteristics and behavior of the NAO/AO.
- o Conduct an intercomparison/evaluation of the various techniques for "downscaling" information from coarse resolution century integrations to the local and regional levels. Use the ENSO cycle as the "large-scale" climate forcing.
- o Based on the formalized evaluation, apply the best technique(s) for the next round of assessments of how climatic extremes are likely to change over the next century and the potential impact on the United States in terms of hurricanes, floods and droughts.
- o Organize paleoclimate, contemporary climate, and related data and information about past abrupt climate changes
- o Identify critical indicators/evidence needed to assess whether we are currently experiencing a climate transition.

Ongoing plans and activities

The research foci discussed above address the most important questions about natural climate variations and their possible modification by climate change because of their significance as sources of climate prediction uncertainty. All are research efforts for which targeted resources will produce scientific results over the next five-years that will impact significantly the reduction of those uncertainties, although for several, additional research will be required.

The scientific strategy to attain these objectives requires long-term base-funded observation and research activities, including: theoretical and modeling studies using established dynamical constraints to project the behavior of the climate system; basic research tools, such as a hierarchy of process models, diagnostic analysis of climate information, long time series of *in situ* and space-based observations of weather and climate variables, clouds, precipitation, and ocean circulation; and regional studies of current climate change impacts. Current base-funded support for these activities comprises elements of a number of ongoing and planned interagency activities such as: Global Water Cycle/GEWEX, CLIVAR (Climate Variability), GLOBEC (global change and marine ecosystems), ESH (Earth System History), SEARCH, etc. This work will also be enhanced by analysis and synthesis of existing data sets from large field experiments completed during the 1990s and existing satellite data sets.

Deliverables

- o Predictions with significantly reduced uncertainty of (i) ENSO cycle, including associated extreme weather events within the US and around the world; and (ii) climate variability associated with major modes of atmospheric/oceanic oscillations, such as the Pacific Decadal Oscillation and the Arctic Oscillation/North Atlantic Oscillation, and the changes that may be expected under climate change.
- o Capability for downscaling climate information to regional spatial scales, in order to produce probabilistic estimates of change in the distribution, frequency and

intensity of extreme weather events that may result from natural variability and human influences on climate.

- o Assessment of the scope for possible abrupt climate transition or change that could result from the non-linear (chaotic?) interplay between ocean, atmosphere, land surface, and ice.

d. Climate Modeling: Climate prediction and enabling research

Computer simulation is one of the most important components of a comprehensive climate research program. Because the Earth system cannot be isolated and studied in a physical laboratory, models are an essential tool for synthesizing observations and theory to investigate how the system works and how it is affected by human activities. The continued development and refinement of computational models that can simulate the past and future conditions of the Earth system is crucial for developing capabilities to provide more accurate projections of future change. Comprehensive climate models represent the major components of the climate system (atmosphere, oceans, land surface, cryosphere) and the transfer of water and energy among them. Current research has demonstrated that more accurate simulation and prediction that reduces uncertainty about projected future change requires the inclusion of more process, particularly the biological and chemical processes that influence the atmospheric concentrations of carbon. Accordingly, future projections must be made with Earth system models that simulate more than the climate alone.

The four principal US agencies that support climate model development and application commissioned the National Research Council (NRC) to analyze US modeling efforts as well as to suggest ways that the agencies could further develop the US program so that the need for state-of-the-art model products can be satisfied. These reports, The *Capacity of US Climate Modeling to Support Climate Change Assessment Activities* (1998) and Improving *the Effectiveness of U.S. Climate Modeling* (2001), provide valuable guidance on how to improve US climate modeling efforts. Also, an Ad Hoc Working Group on Climate Modeling charged by the Subcommittee on Global Change Research (SGCR) prepared the report, *High-End Climate Science: Development of Modeling and Related Computing Capabilities* in late 2000.

Programmatic Objectives

- o Capitalize on the strong US basic research enterprise while simultaneously producing the routine and on-demand products demanded by the impacts, assessment and policy communities. Diverse basic research, performed principally by single investigators or small groups in academia, is the primary source of new basic knowledge about the climate and Earth system. Provide a venue for these researchers to interact with a high-end modeling center that can make use of new information; and
- o Develop the capability to produce routine and on-demand high-end climate model simulations and projections required for other communities.

Proposed Strategy

- o Establish two complementary high-end modeling centers to address the promise and problems identified above. The first, a high-end research center, would be charged with developing an open and accessible modeling system that integrates basic knowledge from the broad, multi-disciplinary basic research community. The second research center would compliment the first by focusing on model product generation for research, assessment and policy applications as its principal activity;
- o Establish and maintain links between the two centers so that the operational needs can be communicated to the research community and the research progress can be transferred into the operational products. A joint Advisory Committee will be established to provide the centers with advice and recommendations. A visiting scientist exchange program will be developed to promote cooperation in all aspects of the center's research such as model framework development, the adoption of standards, the joint evaluation of models and physical parameterization schemes;
- o Focus efforts on software engineering with the development of modeling frameworks to improve the compatibility and portability of model codes, thus ensuring that software advances can be more easily shared among centers and laboratories; and

Ongoing plans and activities

In response to the reports, four agencies initiated activities to strengthen the U.S. modeling infrastructure and address several of the high-priority needs that the NRC and Ad Hoc committees identified.

- o The Community Climate System Model (CCSM) project is dedicated to the development of a state of the art climate system model for research into climate processes and climate applications. While the CCSM core project teamed is located at NCAR, the CCSM was established through the self-organization of the climate modeling research community with the encouragement of the Federal agencies responsible for modeling. Soon after it was established, CCSM became a magnet for a wide range of both model development and model application research. The model currently includes components that represent the atmosphere, ocean, land and sea-ice physical processes. Current research includes addition of both marine and terrestrial biogeochemical processes to the system. Additional plans are to include atmospheric chemical processes to model changes in greenhouse gases and aerosols. Computational resources for the CCSM activity are available through the Climate Simulation Laboratory at NCAR and additional resources made available through DOE. The development process of the CCSM is governed by a Scientific Steering Committee, which is composed members, from both inside and outside of NCAR and four from the university community. The SSC receives advice from the CCSM Advisory Board, which is composed of members from universities, national laboratories and NCAR.
- o The Operational Research Center's core component is NOAA's Geophysical Fluid Dynamics Laboratory (GFDL) at Princeton, New Jersey. GFDL has played

a central role in climate research. Much of the pioneering work in climate change, stratospheric modeling, seasonal forecasting, ocean modeling and data assimilation, and hurricane modeling was conducted there. This core research capability will be enhanced to enable product generation and policy related research. Additional research capabilities in carbon cycle, water resources, atmospheric chemistry, paleoclimate, oceans and climate, and integrated assessment modeling will be leveraged through collaborations with GFDL's existing partnerships with Princeton University and Columbia University's Lamont-Doherty Earth Observatory.

- Interagency investigations of the suitability of distributed memory, high-end computers for climate modeling are now underway. (DOE SciDAC, NASA CAN, NSF ITR, NOAA HPCC).

Deliverables

- The venue to provide for interactions within the climate research community is through the proposed research-oriented modeling center; this operates in a way that is suited to the culture of the small-project investigator. Although aligned with the basic research community, the research center will be product-driven in that it will develop, maintain and distribute a state-of-the-art modeling system.
- The operational center will fill this role as the center of a climate modeling service. It will grow out of NOAA's charter to provide the US with prediction products. Although its mission is operational, experience at the ECMWF has shown that high-quality operational centers require a significant in-house research activity that can collaborate and interact with the external research community and transfer knowledge into the center. It will utilize NOAA's delivery mechanisms for climate information that already have been established, e.g. the NWS, the IRI, the RISA program. It will also build new links to the policy community and to the private sector involved in carbon mitigation strategies and long range economic planning.

B. LONG-TERM MONITORING SYSTEMS: THE FOUNDATION FOR RESEARCH, MODELING AND INFORMED DECISIONS

The climate science community has developed an extensive set of requirements to meet the needs for climate observations. For some variables, new observational techniques will have to be developed and employed. For others, it is possible to utilize existing observing capability. Additional effort is required to produce satisfactory climate data records from operational data. We recommend a re-dedication of our national efforts to develop and to sustain the essential components of a comprehensive global observing system, involving oceanic, atmospheric and land-based (ecosystems and land cover) elements capable of meeting climate requirements.

Over the past decade a number of basic principles have been developed for the delivery of long-term data with minimal space- and time-dependent biases. A 1999 NRC study *Adequacy of Climate Observing Systems* addressed the adequacy of the climate observing system and endorsed a suite of climate monitoring principles. These principles are critical for climate observations, and have also been endorsed by the United Nations Framework Convention on Climate Change, and in the recommendations for a Global Climate Observing System (GCOS). Briefly described the NRC recommendations include::

a. **Management of Network Change:** Assess how and the extent to which a proposed change could influence the existing and future climatology.
b. **Parallel Testing:** Operate the old system simultaneously with the replacement system.
c. **Metadata:** Fully document each observing system and its operating procedures
d. **Data Quality and Continuity:** Assess data quality and homogeneity as a part of routine operation procedures.
e. **Integrated Environmental Assessment:** Anticipate the use of data in the development of environmental assessments.
f. **Historical Significance:** Maintain operation of observing systems that have provided homogeneous data sets over a period of many decades to a century or more.
g. **Complementary Data:** Give the highest priority in the design and implementation of new sites or instrumentation within an observing system to data-poor regions, poorly observed variables, regions sensitive to change, and key measurements with inadequate temporal resolution.
h. **Climate Requirements:** Give network designers, operators, and instrument engineer's climate monitoring requirements at the outset of network design.
i. **Continuity of Purpose:** Maintain a stable, long-term commitment to these observations, and develop a clear transition plan from serving research needs to serving operational purposes.
j. **Data and Metadata Access:** Develop data management systems that facilitate access, use, and interpretation of data and data products by users.

The United States actively supports the Global Climate Observing System (GCOS) through its participation in and support of the GCOS networks, and through its support of related climate observing activities. The United States recognizes that international cooperation both in the data collection and sharing of the information is essential to provide the climate information required by the United Nations Framework Convention on Climate Change .

A systematic inventory of the U. S. climate related observing systems was just completed. A comprehensive report was prepared as directed by UNFCCC Decision CP/1999/L.3, which requested all Annex I Parties to provide a detailed report on systematic observations in accordance with the UNFCCC reporting guidelines on global climate change observing systems adopted by UNFCCC Decision CP/1999/L.4. The principles of this report are based on the climate observing requirements for observing networks, practices, and data management as agreed to internationally in documentation such as "The Plan for the Global Climate Observing System (GCOS)," Version 1.0, May 1995 GCOS-14 (WMO/TD-No. 681).

1. Atmospheric observations

An essential set of baseline climate reference surface stations will be accelerated and enhanced in the US and in all countries. They will provide high priority surface climate measurements and include temperature, precipitation, cloud cover, humidity, soil moisture, and ground temperatures. The GCOS (sponsored by WMO, IOC, UNEP, and ICSU) has identified a GCOS Surface Network (GSN) of approximately 1000 locations worldwide where observations are required for climate monitoring. These stations provide a baseline for global change, and will further serve as calibration/validation sites for space-based retrievals of surface climate measurements. This will both enhance the regional coverage of key climate parameters from *in situ* data and allow expansion of surface data to the global scale.

The GCOS Upper Air Network (GUAN) consists of about 150 stations selected to produce a homogeneous global distribution. The stations, which are a subset of the larger WMO World Weather Watch Global Observing System, are intended to meet both weather and climate objectives. The network provides global fields of key climate parameters (e.g., temperature, humidity, and winds) and is crucial to supporting both the monitoring of the climate system and the research needed to understand its variability and ultimately to make climate predictions.

At present greenhouse gas sampling principally involves clean maritime air collected at surface sites. Atmospheric CO_2 sources and sinks are estimated by global models that rely on such observations and consequently these estimates are poorly determined. Over the next 3-10 years, global satellite retrievals of column CO_2 are expected to become increasingly quantitative and help improve flux estimates. We will exploit available synergies that could be obtained by simultaneously measuring compounds such as CO_2, tropospheric ozone, and aerosols.
The WMO Global Atmosphere Watch (GAW) currently consists of a global array of about 20 comprehensive stations and about 380 more specialized observing sites at which only very limited measurements of atmospheric constituents are made. Four of the GAW sites are operated by the US.

Shortcomings
While the national system has made a start in the design and operation of a climate reference network, the GCOS experience to date indicates that developing countries in particular have often been unable to maintain the observing schedules, or to transmit the information effectively. Approximately half the global network does not meet the observing and reporting protocols.

Monitoring reports consistently indicate that only about two thirds of the stations are fully or partially compliant with the observing and reporting requirements. These inadequacies have led to large uncertainties in trends of tropospheric temperature and humidity in particular.

The global network is currently adequate to characterize global, long-lived, greenhouse gas levels, but inadequate to determine sources and sinks at less than global scales. In all cases, the network of *in situ* measurements is inadequate for climate attribution studies. Long-lived greenhouse gases are not measured adequately over continents as analyses of model sensitivity show. However, local meteorology and sources make interpretation of continental surface concentrations alone quite difficult. Future satellite measurements of column-integrated CO_2 require enhanced modeling skill. Furthermore, satellite measurements will need ground-truth to ensure that apparent gradients and fluxes are not spurious.

The emissions producing ozone and aerosols are poorly known, especially in regions like Asia, where they are expected to increase rapidly with industrialization. Sampling and interpretation of pollutant emissions have not been adequate, and simulation of the processes controlling ozone and aerosol must improve in order to recommend reasonable amelioration. The three-dimensional distribution of tropospheric ozone is not well understood, and location is a large factor of its deleterious effects. Continuous measures of volcanic aerosol amounts in the tropical stratosphere are not in place to sample the effects of the next climate-altering eruption. The tropospheric ozone distribution is not adequately described by current networks, which are spotty in time and space.

Proposed Strategy

- Working with international organizations and through bilateral agreements, provide additional support for instrumentation for observations and for training of technicians in developing countries. Support regional working groups and initiatives such as the GCOS Regional Workshop Program aimed at designing and developing national contributions to the observing systems. Accelerate the installation of a US climate reference network and ensure that all high priority surface climate measurements are included in the network.
- Place new WMO Global Atmosphere Watch (GAW) in priority sites to measure pollutant emissions in specific regions (e.g., at islands downwind from Asia with instrumentation to measure relevant tropospheric compounds such as ozone, aerosol compounds and precursors, soot and optical effects, and tracer gases, carbon monoxide and organics). Add new stations to measure aerosol and ozone in poorly sampled regions of the globe.
- Work in conjunction with international partners to reestablish and support the benchmark upper-air network for the long-term. The US should particularly address stations located in data-sparse areas (e.g., remote islands, Latin America, Africa) to ensure the supply of expendables, communication equipment, and training for technical staff and should work with other countries to establish a system which would ensure the continuation of such support. Increase support for the national and international surface and free-air sampling programs. New instruments to directly measure free tropospheric values of greenhouse gases from the ground and from aircraft need to be developed as well as those to determine isotopic composition of CO_2 without requiring an air sample. For example, the upward looking infrared spectrometers technology developed for stratospheric work can be applied to obtain accurate column-integral CO_2; it should simultaneously measure other species. Ancillary measurements, including of the variable effect of humidity in diluting CO_2, and measurements of carbon monoxide, nitrous oxide, and methane will be available and very useful. Installations may be staged, starting in South and

North America. A combination of *in situ* measurements with sufficiently accurate satellite measurements will be required for future work on global sources and sinks. Surface networks should be coordinated and inter-calibration improved. CO_2 measurements should be coordinated with studies of the intercontinental transport and buildup of other active greenhouse pollutants.

Ongoing plans and activities
The present status and immediate future plans regarding these observing systems are compiled by the National Oceanic and Atmospheric Administration on behalf of the United States Government. The report was published in August 2001 under the title: "The United States detailed National Report on Systematic Observations for Climate: United States Global Climate Observing System (US-GCOS) Program".

Deliverables
- o Complete internationally sponsored global networks for surface and upper air measurements.

2. **Oceanographic Observations**

The ocean's role in the climate system includes both storage and transport; the ocean is the main memory of the climate system and is second only to the sun in effecting variability in the seasons and long-term climate change. We need to determine whether the thermohaline circulation is slowing, as some models predict, whether El Niño is looming, and to map other regional changes of vital interest to the health of the ocean. The ocean is both source and sink for CO_2 and contains 50 times more carbon than the atmosphere. Sea level change is one of the most important consequences of climate change; it impacts essentially every coastal nation. Accurate observations are needed as data for climate models, for determining the present rate of change in ocean structure and for alerting us to any unforeseen changes in ocean circulation with potential climate impacts. It is anticipated that there will be future needs for tracking of additional variables (e.g., nutrients, ocean blooms, phytoplankton, pollution, dissolved CO_2 and other trace constituents).

Shortcomings
An observing system that can accurately document climate-scale changes in ocean heat, carbon, and sea level change is not in place. Currently, it is estimated that the ocean observing system, based in large part on research programs, is providing only a fraction of what is needed. Some effective subsystems have recently been developed to monitor some aspects of the ocean, the most notable being the TAO array of moored buoys in the Pacific Ocean. Major issues remain in better determining fields of sea surface temperature and surface fluxes. There is also a crucial need to systematically provide continuous, three-dimensional fields of variables for the ocean: heat content, salinity and currents. Knowledge of the distribution and changes in the heat storage in the upper ocean (above the thermocline) is a key element in understanding why observed climate variations at the surface have occurred. Sea ice is very important to climate change. Areal extent can be monitored from space but thickness, mass and volume are *in situ* tasks, and data are not

routinely available. The requirements for ocean observations for climate have been well documented, the relevant technology is available, and the international community is mobilized through GCOS and the Global Ocean Observing System (GOOS) to implement key elements of the system.

Proposed Strategy
Current initiatives include arrays of autonomous drifting floats at the surface and profiling instruments at depth, moored arrays for temperature, salinity, and currents, tide gauge stations, and observations from ships which need to be extended to all oceans; proven satellite missions (e.g. altimetry, scatterometry, ocean color, precipitation, sea surface temperature, etc.) which need to be continued in both research and operational modes, and systems of data assimilation (initially via the Global Ocean Data Assimilation Experiment, GODAE) and analysis which also require considerable resources. Initially a goal should be to adequately determine upper ocean fields on a monthly basis although some users require weekly or higher frequency data. Other major parts of the ocean vary slowly and need less frequent observations. The deep ocean, for example, needs annual or perhaps 5-yearly observations. Ocean station time series at a few key locations can help in monitoring physical climate as well as carbon. Continued investment in telecommunications and information technology is essential to ensure the timely delivery of critical ocean climate data.

Ongoing plans and activities
The present status and immediate future plans regarding these observing systems are compiled by the National Oceanic and Atmospheric Administration on behalf of the United States Government. The report was published in August 2001 under the title: "The United States detailed National Report on Systematic Observations for Climate: United States Global Climate Observing System (US-GCOS) Program".

Deliverables
- US leadership is needed to implement national and global ocean components to obtain observations of key ocean variables including air-sea fluxes of heat, freshwater, and carbon; upper- and interior ocean temperatures, salinities, and currents; sea level, and sea ice extent and thickness.

3. <u>**Terrestrial Observations**</u>

The terrestrial components of the observing system measure hydrological, cryospheric, and ecosystem variables, many through the Global Terrestrial Observing System (GTOS). A global observing capability for atmospheric and hydrologic variables uses satellite and *in situ* systems to support interannual and decadal studies. Water cycle observations are currently poorly coordinated. Given the importance of water for understanding climate forcing and variability, and the strong coupling that exists between the land, ocean and atmosphere it is necessary that elements of the terrestrial observing system be considered in a fully integrated fashion. The largest variations over land occur through the amount of moisture in the soil and such variations are vitally important to agriculture and climate. In particular, hourly precipitation and daily soil moisture fields from surface and space-based indicators are required. Hydrological observations also include surface and groundwater, river flows, lake levels, and related variables. Cryospheric variables are collected as parts of glacier and permafrost networks, both requiring additional sampling sites to be more representative. At present, a comprehensive system to observe elements of the global water cycle is just being implemented. Ecosystem observations are made through a small number of comprehensive sites and a larger number of more specialized locations. For example, the Global Observation of Forest Cover (GOFC) program is an international initiative under GTOS to secure the necessary satellite and *in-situ* land cover related observations in support of global change research and natural resource management. GOFC supports global assessments of carbon and ecosystems in three implementation areas: land cover, fire, and biophysical observations through better articulation of the observation requirements, determination of the accuracy of satellite data products through a network of validation sites, and improved access to data and information products tailored to support decision and policy making.

Shortcomings
The GTOS involves a large and disparate community. Many individual observing components are being developed, but international participation is not adequate to meet the requirements. The US lacks a federal focal point for terrestrial climate observations to coordinate the disparate observational activities underway in the various federal agencies.

Proposed Strategy

- The US should take a lead role in developing those observing system components that are of highest priority to meet climate needs. These include aspects of the Global Terrestrial Networks for glaciers (GTN-G), permafrost (GTN-P), ecosystems (GTN-E), and global forest cover (GOFC). The US agencies will coordinate their observing activities more effectively.

Ongoing plans and activities
The present status and immediate future plans regarding these observing systems are compiled by the National Oceanic and Atmospheric Administration on behalf of the United States Government. The report was published in August 2001 under the title: "The United States detailed National Report on Systematic Observations for Climate: United States Global Climate Observing System (US-GCOS) Program".

Deliverables

- US leadership is needed to implement a suite of terrestrial observing components to obtain crucial measurements of terrestrial variables related to carbon cycles, surface hydrology (including precipitation, evaporation, runoff, stream-flow and soil moisture), ecosystems, and the cryosphere (including snow cover, glaciers, and permafrost).

4. Satellite Observations

The US operates an extensive space-based, remote sensing observation program for elements of the atmosphere, ocean, terrestrial systems, and climate forcing. Satellites provide the primary means of obtaining a global perspective and comparing different parts of the globe. A comprehensive global climate record is not practicable without a major satellite component, but challenges remain in mission continuity and data quality regarding artificial changes from orbital and calibration modifications. The satellite observations, together with complementary *in situ* observations, aim to provide essential information on how climate is varying and changing.

Shortcomings

The science community has identified key issues with constructing long-term climate records from satellite observations. Thus far the most prominent record has been the one constructed from the MSU (Microwave Sounding Unit) temperatures, but even those have undergone major revisions and further substantial revisions are being reported. Follow-on satellite missions often have a somewhat different orbit and different time-of-day sampling. Orbits decay unless continually boosted, and there is substantial drift in the time of observations for polar orbiting satellites. In the past, instrument calibrations have been altered by the launch and the space environment, and measurements have been affected by other instruments and the platform.

Proposed Strategy

- Satellite missions intended for climate monitoring would be launched into stable orbits designed to minimize drift in time of observation to within 2 hours over the lifetime of the satellite, and/or utilize boosters to stabilize the orbit.
- Sufficient satellites will be operating to enable adequate sampling of the diurnal cycle. Satellites would be launched on schedule, rather than on failure of the previous mission, to ensure overlap of measurements, which is essential for the climate record.
- All instruments would require pre- and post-launch calibration and the existence of a sustained in situ network for an extensive ground truth validation. Resources are needed to improve telecommunications and telemetry capacity.

Ongoing plans and activities

The present status and immediate future plans regarding these observing systems are compiled by the National Oceanic and Atmospheric Administration on behalf of the United States Government. The report was published in August 2001 under the title: "The United States detailed National Report on Systematic Observations for Climate: United States Global Climate Observing System (US-GCOS) Program".

Deliverables

- US leadership to develop and deploy instruments with improved calibration and validation, and to disseminate the critical global observations that will result.
- Development of innovative instruments that have demonstrated promising capabilities, such as those based on GPS technologies, and instruments for carbon observations in the atmosphere and the sea surface; aerosol distribution,

properties, and cloud interactions; and global land surface characterization including forests, managed ecosystems, and the cryosphere.

5. Data Management

Climate reference data set development work is a key step in understanding the observed climate record. Observations relevant to climate have been collected for various other purposes, and may not meet climate monitoring standards. Once the data are collected they often require calibration using appropriate standards, careful and systematic analysis and sometimes, 'data archeology' to produce a reliable time series to detect climate change and attribute these changes to specific causes. In addition, observational uncertainties are required so they can be considered in evaluating the record. Ultimately, the data must be able to represent the true nature of observed changes and variations. In addition to developing climate-relevant data sets, the number one priority for many scientists and decision-makers is access to global data. Data products such as time series based on proxy paleoclimatic date and other data are of prime relevance to climate change.

Shortcomings
Data management and related information services require resources but are often overlooked when programs are planned and implemented. Data volume is expected to increase dramatically, creating challenges of archival, maintenance and effective access to the data.

Proposed Strategy

- o Develop indicators and provide reports on monitoring the health and performance of the climate observing system,
- o Develop and institute consistent and well-designed data management practices to ensure the delivery climate-relevant data of immediate consequence and utility. Additional resources will ensure consistent data management across the broad range of climate variables, value-added data sets, and model products,
- o Implement climate data assimilation and periodic reanalysis, and develop operational capabilities, including new model-based analyses of the ocean and land surface as well as for the atmosphere, and
- o Enhance the capability to deliver climate change relevant data and information to the user community through existing climate extension service programs at the national, regional and state level (e.g., NOAA Regional Climate Centers, American Association of State Climatologists Recognized State Climate Offices, NOAA/NWS field offices, and other federal agencies such as FEMA, USDA, and DOI).

Ongoing plans and activities
The present status and immediate future plans regarding data and information management issues have been compiled by NOAA. The report was published in August 2001 under the title: "The United States detailed National Report on Systematic

Observations for Climate: United States Global Climate Observing System (US-GCOS) Program".

Deliverables

- o Improved climate record by ensuring the integrity and continuity of the observations, their analysis into products, and links to modeling and research activities; and
- o Maintenance of the climate record by state-of-the-art systems for data archival and access.

C. RESEARCH ON ENVIRONMENTAL-SOCIETY INTERACTIONS

The importance of climate change lies mainly in its impacts on natural resources, the economy, and human health. Some regions and assets will be more vulnerable to climate change than others, and taking steps to enhance the resilience of assets that may be unacceptably vulnerable will help ensure economic productivity and the well being of the citizens of the United States and other nations. The regional impacts research component is designed to focus on sensitivity and adaptation, to integrate research on changes in climate with other environmental conditions, and to develop this integrated perspective as a series of decision-making tools. This will not only increase the salience of research, but also identify which unknowns are most important to address from a societal point of view, and thus to help refine the research agenda.

The environmental-society interactions research includes a focus on the regional scale for several reasons. "Regions" - particular places and decision contexts - are the analysis units in which different manifestations of climate change will be integrated with other changes, both environmental and socio-economic. Their scale and characteristics are defined by the problem being addressed. Understanding how multiple environmental forces will interact with economic and social conditions is necessary in order to develop realistic options for managing risks or opportunities that will arise from climate change.
The recommended initiatives build on the foundation of the USGCRP and set the goal of providing information for increasing the resilience of systems threatened by global change.

1. <u>Fostering research on coupled human-environment systems</u>

Regional research has been found to be one of the most effective ways to investigate multiple environmental stresses directly connected with decision makers. In a "place", whether a watershed, urban center, national park, or agricultural region, public and private sector decision makers and natural resource managers must consider not only multiple environmental stresses but other essential factors (competing incentives, tradeoffs, institutional constraints, jurisdictional conflicts, availability of human or financial resources, etc.) in their decision making process. Some decision makers lack

access to information in forms that are applicable to their problems, while others are inundated with information and need assistance in selecting, organizing, integrating resources. To address both problems, state of the art information systems that integrate environmental research results and data on economic and social factors are required.
The 2001 NRC report on *The Science of Regional and Global Change* concludes that there are barriers to promoting regional research, notably within the interagency structures used to plan collaboration and research, and between scientists, policy/decision-makers, and natural resource managers. To foster collaboration both across agencies and between scientists and policy/decision makers, we recommend a focused set of prototype regional investigations that will rely on new incentives and mechanisms. While we acknowledge that it is difficult to dictate collaboration, as rapport and trust must first be developed between individuals, we feel we can promote collaboration between research and decision making cultures to a much greater degree. These programmatic approaches are described below.

Programmatic Objectives
The NRC report recommends the following eight actions to implement an effective research agenda:

- Ensure an "intimate connection" between research, operational activities, and the support of decision making;
- Participate in and support interdisciplinary research relating physical, biological and human systems;
- Plan and implement sustained and integrated observing networks and information systems that transcend traditional agency boundaries;
- Plan to incorporate scientific and technological advances into on-going research and operational programs;
- Develop improved models and new predictive capabilities;
- Develop improved assessment capabilities for integrating scientific knowledge into effective decision support systems;
- Define and carry out programs of regional and sectoral multiple-stress research and demonstration projects; and
- Connect research, education, and outreach.

Proposed Strategy

- Develop formal mechanisms to establish ongoing working relationships between the research community and the decision makers to ensure that the research and assessments will address the specific issues of concern to the decision- making community.
- Develop multi-agency RFPs that stipulate that proposals and projects must be developed jointly between scientists and decision makers with requirements for structured cooperation, communication, planning, and implementation between the scientists and decision makers.
- Develop multi-agency RFPs or other funds for both intramural and extramural researchers and programs under joint control to provide support for integrative activities required above and beyond current activities or programs;
- Reward and promotion incentives for scientists doing interagency research.

Ongoing plans and activities
Carrying out regionally-specific research on the issues related to natural resources productivity, metropolitan regions, and integrated assessment will require contributions from the base program of global change research, as well as new approaches for fostering collaboration across disciplines and areas of research, across the agencies, and among researchers and decision and policy makers. Contributions from multiple agencies will be required, with each agency providing expertise and products consistent with its own mission. A number of existing agency programs have supported pilot regional research projects. Experience of these efforts will be evaluated and used to guide development of an integrated interagency RFP for different regional groups related to the focus areas of the initiative.

Deliverables
- Fostering regionally-specific integrated research will empower local, state, and regional decision makers and resource managers with adaptation, mitigation, and management strategies to optimally benefit from the positive aspects of global change and effectively with its detrimental effects by ensuring that scientists work directly with decision makers so more mature research is planned and executed that assists them in making immediate and near-term decisions.
- This initiative will provide the capability to determine which regions, and within those regions, which systems, are most resilient (and which are most vulnerable) to multiple environmental changes. Knowledge and tools needed to respond in a timely manner to environmental changes so that benefits can be maximized and costs of adaptation or response to change can be reduced will also be provided.

2. **Integrating scientific knowledge into effective decision support systems**

Integrated decision support systems for climate change assembles knowledge from a diverse set of sources, relevant to one or more aspects of the climate change issue, for the purpose of gaining insights that would not otherwise be available from traditional, disciplinary research. An idealized integrated assessment modeling system addresses questions ranging from emissions of greenhouse gases to atmospheric composition to climate to effects of human and natural systems.

Research Objectives
- Integrate technology and economics with other system components, particularly the description of energy technology in integrated assessment models. Develop detailed regional descriptions of technology resources, institutions and opportunities, and the ability to describe transition pathways – roadmaps - for technology transitions from the present to the future.
- Develop alternative approaches for aggregating and representing different types of impacts, including those to market economies, informal economies in which barter rather than exchange of money facilitates transactions, and ecological

systems, in which important attributes cannot easily be assigned a monetary value.

Proposed Strategy

- o Develop and sustain three types of integrated assessment groups: large modeling groups, small modeling groups, and research teams which develop specialized information to fill gaps left by other, larger program elements.

Ongoing plans and activities

Integrated assessment models do not yet incorporate impacts on metropolitan areas as distinguished from the economy in general. Yet, important progress is anticipated in three key research areas relevant to metropolitan areas: Air Quality, Water Quality and Quantity, and Extreme Events. An attempt will be made to incorporate this knowledge into the larger integrating framework of assessment models.

Deliverables

- o Deliver the capability to address regional emissions and consequences of climate change in integrated assessment models, facilitated by building international partnerships. Hydrology and agriculture are acutely important to understanding the regional consequences of climate change.

3. **Region and sector level research, analyzing human and natural systems integration**

a. Natural resource regions

We know that several environmental factors are changing. We also know that each of these factors has effects on the Nation’s managed and natural ecosystems and the critical goods and services that they provide such as food, fiber, clean water, energy, and recreation. These changes also have major implications for how decision makers, including resource managers, regional planners, large corporations, small farmers, and rural communities, must manage these resources to maintain their productivity. In this initiative, we recommend research targeted at identifying strategies for maintaining the productivity of natural resources that the nation depends on, such as agriculture, forestry, and water.

This will not only provide direct economic benefits, it will also help preserve watersheds that provide water supplies for many major metropolitan regions, as well as recreation outlets for densely populated areas. Because the challenges to managing these resources vary widely across localities and regions, it is crucial to carry out a substantial portion of this research within localities and regions, working hand in hand with the decision makers and resources managers who need sound, science-based information to make effective decisions.

To address these issues, a combination of field experiments, mechanistic models, and decision support tools and information systems will be developed.

Research Objectives

- Investigate the impacts of multiple factors, including climate change, on natural resources, in particular food production by major U.S. crops.
- Evaluate the response in water use by crops and other ecosystems in a combination of warming and elevated CO_2.

Proposed Strategy

- Implement a field experiment program to experimentally manipulate multiple factors in key (and representative) ecosystems in several regions. Within the next 5 years target the major annual crops: corn, wheat, and soybean, in major agricultural regions. For other systems such as forests, rangelands, and wetlands, initial efforts will target those of most economic consequence (e.g., forests) and those that are potentially most sensitive and unique (e.g., national parks, wildlife refuges, wilderness, and other protected areas).
- Improve the major crop models so that they treat effects of multiple environmental changes, and extreme conditions, on yield and water use.
- Implement a national, pilot project on integrated, multidisciplinary modeling of impacts of multiple changes on ecosystems. As a prototype, develop a comprehensive and modular computer model of a terrestrial system, including responses to multiple changes and human management, such as fire suppression.
- Develop, test, and evaluate plant response and water quantity/quality prediction models for land management at different scales.
- Develop an integrated framework to guide selection and application of these models and related decision support tools.
- Develop a central point of access and repository for all plant, ecosystem, and watershed information, data, and management models and decision support tools.
- Promote and coordinate application of these information-bases, models, and tools for watershed management, through training and support.

Ongoing plans and activities

The experiments proposed here will focus on multiple attributes including: plant water use efficiency, ground/surface water quality, impacts on pests and invasive species, and the multiple uses to which landscapes are put, such as agricultural, recreational, and other purposes that affect carbon storage.

Deliverables

The products will be developed within the context of regional economic markets and population dynamics. Specific products and deliverables will include:

- Crop models that include responses to multiple environmental changes (CO_2, ozone, temperature, and precipitation), based on up-to-date research, will be developed.
- An advanced ecosystem model (pilot effort) will be developed for one (or a few) natural system(s) important to the Nation. This work will be the foundation for a

new national capability in modeling and predicting effects of climate change on our natural resources.

- A capability to support collection and exchange of regionally-based information on potential climate change effects and model development/application that: a) serves as a clearinghouse for information, databases, models and decision support tools; b) provides an integrated framework to guide selection and application of models and support tools for land and watershed managers; c) provides training, technical support, documentation, evaluation and user manuals for modeling packages, and d) maintains pointers to ongoing successful applications for management under uncertainty.

b. <u>Metropolitan regions</u>

An important focus of the recommended research options is on urban/metropolitan areas. An increasing percentage of the American people choose to live in major urban/metropolitan areas, particularly along the coasts. An important characteristic of these urban communities is that their economic viability and well-being is closely linked with the larger watersheds within which they are situated and the natural resources in the watersheds.

Metropolitan areas represent an ideal place within which to conduct policy-relevant research that integrates the influences of multiple factors (e.g., climate change; population changes; land-use change) on multiple effects (e.g., the air we breathe; the water we drink). It also provides an ideal test-bed within which to analyze the critical interactions between human and natural systems.

Previous research and assessments have identified priority challenges in urban/metropolitan areas that are sensitive to climate change and other important factors, including:

- Air quality and related effects on heat stress and cardio-respiratory disease
- Water quantity and quality and related health effects
- Extreme events and weather-related morbidity

The recommended initiative will include a process to identify other emerging decision making and policy challenges, develop the observing and information management infrastructure that is missing, and thus integrate, share, and apply knowledge to decision making.

Research Objectives

- Determine the quantitative effect of climate change and other factors on ambient concentrations of tropospheric ozone and particulate matter (e.g., black carbon);
- Identify the geographic areas that will experience the largest changes (positive and negative) due to global change and the areas that will fail to attain desired levels of air quality due to climate change;
- Assess the consequences of climate change on four aspects of water quality: drinking water infrastructure, wastewater treatment, surface water quality, and surface/groundwater interaction;

- o Examine the potential for adaptive responses to protecting drinking and surface water for human and ecosystem uses in metropolitan areas in the U.S.;
- o Develop the framework to integrate questions characterizing meteorological factors (historically and in a predictive mode) with contextual and analytical questions designed to make more precise assessments of vulnerability to extreme events and identify options for preparations to enhance resiliency.

Proposed Strategy

- o Develop a set of meteorological variables needed for air quality simulations, and analyze the statistical relationships between weather and tropospheric ozone and particulate matter (PM);
- o Develop baseline and future emissions scenarios for ozone and PM using scenarios of economic growth, energy demand, population growth, vehicle miles traveled, policy scenarios, and information about anthropogenic and biogenic emissions; and
- o Simulate base case and future concentrations of ozone and PM;
- o Since climate change and variability will affect water quality primarily through changes in runoff, we recommend evaluating how climate change will affect runoff. To that end climate models will be used to predict regional changes in both precipitation and evapotranspiration and the output will be integrated with output from land use choices models. In addition, changes in storm intensity, the effects of wetlands and riparian buffer zones and the diluting effects of runoff will be modeled;
- o We recommend a "staging strategy" where, when possible, increases in the risks of certain kinds of extreme events are first identified in seasonal forecasts, the general timing of events within a season is identified through model simulations at lead times of roughly five days to two weeks, then as lead time to an event is reduced to approximately two days or less, increasingly detailed forecast information is provided as to event intensity, timing, and location. This approach will be coupled with observations, modeling and research to identify the institutional and socio-economic factors that account for increases in sensitivity to the timing and magnitude of extreme events.

Ongoing plans and activities

This integrated research approach would capitalize on existing plans to apply recent advances in understanding extreme events, such as coastal storms, and recent advances in modeling and data assimilation, to produce detailed estimates of the range of possible outcomes of relevant meteorological variables in target regions at lead times from a season down to hours. Local conditions, as well as the needs of end users in target regions, would then be used to estimate the probabilities of extremes of quantities most relevant to those end users (such as stream flow or heating degree days).

Deliverables

The products from this initiative would be nationwide assessment reports that quantify the:

- effects of climate change on ambient air quality in selected major U.S. metropolitan areas,
- effects of changes in air quality on human health in multiple metropolitan areas, extent to which wastewater treatments costs will be affected by climate change and changes in extreme precipitation events,
- effects of climate change and climate variability on drinking water quality,
- effects of climate change on water-borne diseases in multiple metropolitan areas, and
- effects of climate change and climate variability on weather-related morbidity.

Decision-support tools would also be produced to help public health officials determine appropriate adaptive response strategies, and to evaluate the extent to which these responses at the societal or individual level could reduce the impacts of climate change on human health and increase the resilience of the public health care system to climate change.